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AN 8 GeV LINAC AS THE BOOSTER REPLACEMENT IN THE FERMILAB POWER UPGRADE[*]

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Abstract

Increasing the Fermilab Main Injector beam power available to the high-energy neutrino experiments above ~1.2 MW requires replacement of the 8 GeV Booster by a higher intensity alternative. Earlier, rapid-cycling synchrotron and linac solutions were considered for this purpose. In this paper, we consider the linac version that produces 8 GeV H- beam for injection into the Recycler Ring or Main Injector. The new linac takes ~1 GeV beam from the PIP-II linac and accelerates it to ~8 GeV in SRF structures. The linac components incorporate recent improvements in SRF technology. The linac configuration and beam dynamics requirements are presented. Injection options are discussed. Research needed to implement the Booster replacement is described.

INTRODUCTION

The PIP-II project will provide a 800 MeV proton beam with cw capability, with beam power up to the MW level available for user experiments [1]. However, the amount of beam that can be transmitted to the Main Injector (MI) is limited by the 0.8—8.0 GeV Booster capacity. The next Fermilab upgrade should include a replacement for the Booster [2]. The upgrade could be based on a continuation of the 800 MeV linac to 2—3 GeV followed by either a Rapid Cycling Synchrotron (RCS), or continuing the Linac to 8 GeV. While an 8 GeV Linac would be expected to be expensive, it may be made relatively affordable by using relatively inexpensive ILC-style cryomodules that use 1300 MHz SRF cavities, that have already been designed and mass-produced.

In this note we will focus on the 8 GeV Linac option. We begin with some discussion of the beam requirements and potential layouts for the Linac. Constraints on accelerating gradients and magnetic fields are discussed.

LINAC SCENARIO REQUIREMENTS

The Fermilab Proton Improvement Plan II (PIP-II) provides a new 800 MeV superconducting rf (SRF) Linac that replaces the previous 400 MeV Linac, enabling higher intensity injection into the Fermilab Booster and providing 800 MeV proton beam to other experiments. The primary purpose of PIP-II is to provide enhanced beam power delivery from the Main Injector to DUNE (Deep Underground Neutrino Experiment) [3]. This is enabled by increasing the beam energy and intensity delivered by the Linac to the Fermilab Booster and increasing the Booster cycle rate. Table 1 shows high-level parameters of the Fermilab beam to DUNE before and after PIP-II, as presented in the Fermilab PIP-II Design Report. PIP-II increases the Booster cycle rate to 20 Hz and the beam intensity to 6.6×10^{12} protons/pulse, enabling beam power of ~1—1.2 MW at beam energies of 60 to 120 GeV.

Further improvements will require replacement of the Booster with a higher-capacity injector. This replacement should provide substantially higher intensity to DUNE. The initial design specification for the upgrade is that it should enable at least ~2.4 MW from the MI [4]. High-level performance goals are presented in Table 1.

Table 1: High-Level Parameters for PIP, PIP-II and the Booster Replacement Linac (BRL)

Parameter	PIP-I	PIP-II	BRL	Unit
Linac Energy	400	800	8000	MeV
Beam Current	25	2	2	ma
Pulse length	0.03	0.54	2.2	ms
Pulse Rep. Rate	15	20	20	Hz
Protons/pulse	4.2	6.5	27.5	10^{12}
8 GeV beam power	80	166	700	kW
Power to MI	50	83-142	176-300	kW
MI protons/pulse	4.9	7.5	15.6	10^{13}
MI cycle time (120 GeV)	1.5	1.2	1.2	s
MI Power to DUNE (120 GeV)	0.7	1.2	2.5	MW
8 GeV other users	30	83	500	kW

LAYOUT

The BRL must take beam from the PIP-II Linac into the MI/RR. The configuration is constrained by the fixed locations of PIP-II and its proximity to the MI. Figure 1 shows a possible scenario. The PIP-II Linac is extended to ~1 GeV by adding 2 cryomodules within the lattice at the end of the PIP-II tunnel, using drift spaces reserved for future extensions. The beam exiting that Linac is bent at ~45° into a 1→2.4 GeV linac, which uses ~10—12 PIP-II 650 MHz cryomodules, requiring ~120—150 m. The total length available is ~ 290 m; the additional length will be used for optics matching and collimation. The transition energy depends on future design optimizations and applications; we consider 2.4 GeV as an initial choice.

The beam then goes through an achromatic bend of approximately 105° to be pointed toward injection into the

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Recycler Ring (RR) at MI-10. The following ~500 m transport includes a 2.4→8 GeV pulsed linac, consisting of LCLS-II-style 1300 MHz cryomodules [5]. and takes the beam toward the MI at MI-10. The 2.4→8 GeV pulsed linac requires ~ 20 cryomodules, which occupy ~250m.

The facility will include transfer lines for intensity frontier experiments at ~1 GeV, 2.4 GeV and 8 GeV.

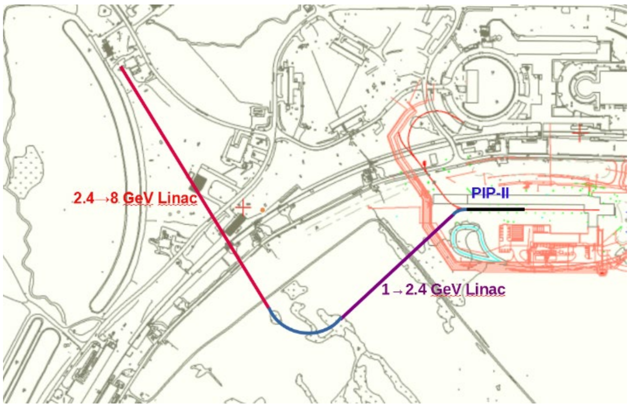

Figure 1: Layout of the 8 GeV linac from PIP-II to the MI.

SRF COMPONENTS

The BRL will contain 650 MHz and 1300 MHz cryomodules. Recent improvements in cavity performance by nitrogen doping and low-T cavity bake will be incorporated into the designs [6, 7, 8]. Parameters of the resulting SRF systems are presented in Table 2. Figure 2 shows cross-sections of the cryomodules, displaying cavities, couplers, and other components.

Table 2: SRF Parameters

Parameter	650 MHz	1300 MHz
β (v/c)	0.9	1.0
Cells/cavity	5	9
Cavity length	1.04	1.38 m
R/Q	638	1036 Ω
$G=Q_0R_s$	255	270Ω
Gradient E_{acc}	22.6 MV/m	35 MV/m
E_{max}	46.8 MV/m	70 MV/m
B_{max}	88 mT	150 mT
Q_0	6.0×10^{10}	2.5×10^{10}
I_{H-} current	2—5 ma	2—5 ma
Q_L	3.4×10^{7}	1.7×10^{7}
Losses @2K	16 W	65 W
Cavity rf power	120 kW	184 kW
Cavities/cryo	6	8
Cryomodule L	9.9	12.5 m
Cavities needed	60	160
Cryomodules	10	20

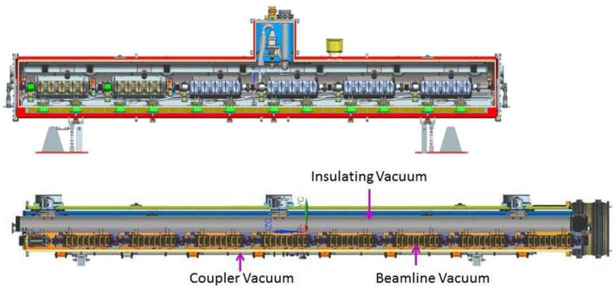

Figure 2: Cross-sections of 650 MHz (above) and 1300 MHz cryomodules, showing cavities and other components [1, 5].

BEAM TRANSPORT

The layout of Fig. 1 shows two bends, which will consist of achromatic transports: 4 90° FODO cells for the 60° bend and 8 90° FODO cells for the 105° bend. The beam is H^-, so it is vulnerable to stripping by magnetic fields, and bending fields must be small enough to avoid stripping. The stripping length can be estimated using this formula of Schrek [9]:

$$L_{strip} = \beta\gamma c\tau = \beta\gamma c\frac{a}{3.197B_t p}\exp\left(\frac{b}{3.197B_t p}\right)$$

meters, where p = is the H^- momentum, B_t is the magnetic field and a and b are parameters fitted from data. Keating *et al.* [10] obtained a = 3.073 10^{-14} and b =44.14 from 800 MeV data. To keep the stripping less than 2×10^{-8} m^{-1} for E_{H^-} =1, 2.4, 8 GeV requires, B_t < 0.28, 0.15, 0.056 T, respectively. ($B_t \propto 1/P_{H^-}$). The bending magnets are designed within those limits. We note that the weak bending field allowed at 8 GeV strongly constrains the subsequent beam transports, including the transport into MI/RR injection.

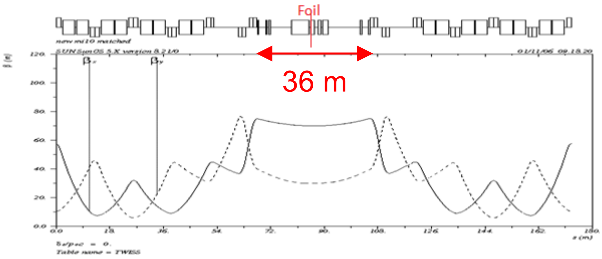

Figure 3: Layout with betatron functions for the RR-10 straight section, adapted for foil injection. A ~36 m segment between focusing quads is reserved for injection kickers, injection bump magnets and stripping foil.

INJECTION

In Fig. 1, The 8 GeV H^- beam is directed toward MI-10, and injection into the MI or the RR in that region should be possible. However, the MI-10 straight section has been designated as the location for extraction of 120 GeV MI beam toward the LBNF target [11]. That extraction system precludes direct injection into the MI. Therefore, our baseline injection scenario would be foil injection into RR-10. The straight section must be modified to include a large beam size at the foil (large β_x, β_y), and incorporate kickers and foils (see Fig. 3) [12].

High intensity multiturn H^- injection into the RR/MI, with injection painting and foil heating, was simulated by Drozhdin *et al.* [13] and further explored by Neuffer [14]. Injection requires ~26 ma-ms of beam. At 1—2 mA, this implies 2300—1150 turns. If this were injected in a single pulse, the foil would heat to ~2500 °K, which is unacceptably high. The preferred injection procedure is to split the injection into a number of separate shorter injections, spaced by the pulsed linac rep rate, and then sequentially inject into the ring, while following a foil painting program to minimize the number of foil hits. Figure 4 displays calculations of foil heating in a 6-step injection at 1, 2, 4 ma currents, which reduces peak T to 2200, 1660, and 1250 K, respectively. The 2 and 4 ma numbers are acceptable.

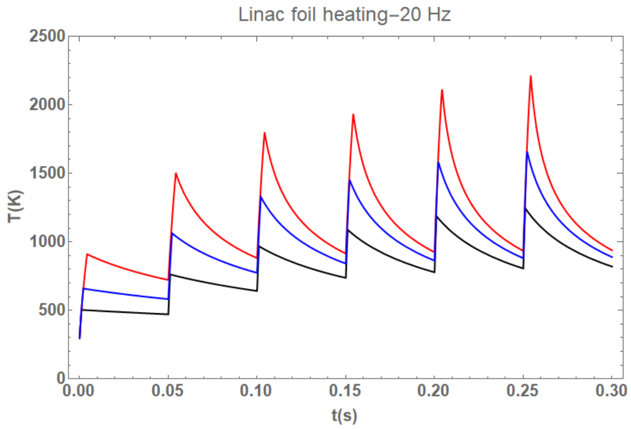

Figure 4: Foil heating in 6-step injection (4.5 ma-ms/step) at 1(red), 2 (blue) and 4 ma (black).

BEAM LOSSES

Beam losses can be a significant limitation in a high-intensity linac. To keep the radioactivation of the beam line components low enough for "hands-on maintenance", activation levels must be below ~100 mrem/hr at 30 cm from a component surface, after extended operation. From previous experience this implies losses of less than ~1 W/m.

A safety limit of ~0.2 W/m would allow relatively unrestricted maintenance.

Important loss mechanisms include [15, 16]:

- Injected beam losses. A fraction of the beam misses the foil and some of the beam that hits the foil will not be fully stripped; these losses should be < ~2%. Most of these should be captured by the injection absorber; uncontrolled losses should be less than ~0.2%.
- Magnetic stripping of H^-. Fields are kept small enough to keep losses less than $\sim 10^{-8}$/m.
- Intrabeam scattering.
- Black body radiation stripping.

The injection region will be designed with a beam dump that captures most of the injection beam losses; this will confine activation to a limited area.

R&D NEEDED

The Booster Replacement program will require a significant R&D program to obtain a timely implementation of the required upgrade. The DOE project process requires detailed designs and evaluations of the proposal and alternatives, which implies both RCS and Linac-based approaches should be evaluated and compared.

The SRF is based on PIP-II cryomodules for the 650 MHz section and ILC/LCLS-2 for the 1300 MHz linac. Improvements based on nitrogen doping, cavity bake, and other surface treatments will need futher development and incorporation into construction.

Other R&D topics that need to be investigated include:

- Simulation and modelling of the complete Linac design, from PIP-II into the MI [17].
- Simulation and optimization of the injection painting and foil heating.
- Consideration of laser-assisted injection and its adaptation to the BRL and RCS scenarios. Laser assisted injection has been considered the eventual preferred procedure for H^- injection, but the R&D needed for implementation has not yet been performed.
- An evaluation of SRF power and wall-plug power requirements for the scenarios, for pulsed and cw operation options, including optimizations, should be developed.
- An alternative injection into a new ~8 GeV storage ring could be considered; this would avoid the MI-10 bottleneck, but at the cost of an additional storage ring. The ring may be needed for intensity frontier experiments.

CONCLUSION

The 8 GeV Linac concept will be developed in more detail in a Snowmass white paper.

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